

## METHOD FOR IN-FURNACE REGULATION OF SO<sub>3</sub> IN CATALYTIC SYSTEMS

### CROSS-REFERENCE TO RELATED APPLICATIONS

This nonprovisional utility patent application claims the benefit of a prior filed provisional application: 60/544,724 filed February 14, 2004, which is incorporated herein by  
5 reference in its entirety.

### Background of the Invention

#### 1. Field of the Invention

The present invention relates generally to a method for reducing byproducts emissions from combustion reactions, and, more particularly, to a method for regulating flue  
10 gas SO<sub>3</sub> in combustion furnaces with catalysts.

#### 2. Description of the Prior Art

##### Acidity decrease

The flue gas of power generation plants has long been recognized as a source of atmospheric pollution. In the combustion of fossil fuels, some of the naturally present  
15 elements are oxidized to form acids, such as SO<sub>3</sub>, NO<sub>x</sub>, HCl, HF, and the like. These acids, especially SO<sub>3</sub>, can become a problem if their concentrations exceed certain thresholds. For example, as the SO<sub>3</sub> concentration increases, the acid dewpoint temperature of the flue gas increases. If the temperature of the flue gas is less than the acid dewpoint temperature of the flue gas, the SO<sub>3</sub> in the gas will condense and react with water to form H<sub>2</sub>SO<sub>4</sub>, causing  
20 corrosion problems inside the furnace. Also, flue gases exiting a furnace cool immediately and SO<sub>3</sub> and other acids in the gas condense, creating localized acid rain, which is the condensation and precipitation of SO<sub>3</sub> and other acids onto the surrounding land with

subsequent corrosion. Excessive  $\text{SO}_3$  will condense into small droplets, creating a visible plume as it exits the furnace, which becomes an esthetic and local political problem. If  $\text{NH}_3$ -like compounds are present in the flue gas, they can react with  $\text{SO}_3$  to form ammonium bisulfate ( $\text{NH}_4\text{HSO}_4$ ) which then fouls the air heater.

5           Thus, a need exists to decrease the acid dewpoint temperature of the flue gases such that the acid dewpoint temperature is lower than the flue-gas temperature in the coolest parts of the furnace, such as the ducts and stack. A further need exists to lower the acid content of the flue gases such that the localized acid rain and other problems associated with high-acid flue gas are minimized.

10            $\text{SO}_3$  increase

The particulate matter carried in the flue gas can be removed by electrostatic precipitators that cause the individual particles to accept an electrical charge and then use that charge to attract them to collector plates for disposal. The efficiency of such electrostatic precipitators is dependent upon the ability of the individual particles to take a charge, that is, 15 the resistivity of the particles. It has been found that the presence of  $\text{SO}_3$  in the flue gas effectively reduces the resistivity of the particles, making them easier to charge electrostatically.

In the combustion of coal, some of the naturally present sulfur is converted to  $\text{SO}_3$ . On the other hand, the effectiveness of  $\text{SO}_3$  in reducing the resistivity of the particulate 20 matter in the flue gas depends upon the concentration of the  $\text{SO}_3$ , with about 15 to 20 parts per million (ppm) giving optimal results. Therefore, precipitator efficiency is affected by the ability to adjust the amount of  $\text{SO}_3$  in the flue gas, regardless of the sulfur content of the coal being burned, to provide an overall  $\text{SO}_3$  concentration in the optimal range.

SO<sub>3</sub> is also produced in SCR (catalyst) installations by the oxidation of SO<sub>2</sub> and often exceeds the optimal 15 to 20 ppm optimal concentrations. The catalyst blends typically used in the SCR to reduce NO<sub>x</sub> to N<sub>2</sub> (in the presence of ammonia) also oxidize SO<sub>2</sub> to SO<sub>3</sub>. The rate of this reaction is strongly temperature dependent and, at higher temperatures, can convert more than 1 percent of SO<sub>2</sub> to SO<sub>3</sub>. High sulfur U.S. coal generates anywhere from 2,000 to 3,000 ppm of SO<sub>2</sub> in the boiler, and therefore can result in 20 to 30 ppm of SO<sub>3</sub> out of the SCR. The problem is that as much as 50 percent, or 10 to 15 ppm, of the SO<sub>3</sub> coming out of the SCR will make it past the scrubber and out of the stack. At about 8 to 10 ppm, depending upon the particulate concentration, SO<sub>3</sub> becomes visible as a blue plume.

Furthermore, SO<sub>3</sub> can also be produced catalytically on other boiler surfaces through interaction with elements/chemicals such as Vanadium.

Therefore, because any SO<sub>3</sub> formed prior to the SCR adds to the effluent SO<sub>3</sub>, reducing the SO<sub>3</sub> formed prior to the SCR is important for reducing the effluent SO<sub>3</sub> and permits the use of SCR for the reduction of NO<sub>x</sub> for gases without generating excessive amounts of SO<sub>3</sub>.

#### SO<sub>3</sub> control

If the SO<sub>3</sub> concentration is too low, the precipitator will operate at less than optimal efficiency. On the other hand, if the SO<sub>3</sub> concentration is too high, the flue gas becomes highly acidic, creating a "blue plume" and contributing to acid rain. In addition, acidic flue gases contribute to corrosion of the pipes carrying the flue gas, and, when combined with NH<sub>3</sub>-type chemicals, can clog the air heater.

Furthermore, an SCR is often only intended to be used for six months per year (during the summer ozone control season), and are bypassed during the winter. This creates seasonal variability in the SO<sub>3</sub> concentrations at the precipitator, in the duct work, and out of the exhaust stack.

5 It is therefore desirable to control the concentrations of SO<sub>3</sub> in the flue gas depending upon whether the SCR is in use or not. SO<sub>3</sub> concentrations approaching 40 ppm produce severe adverse local acid problems that are not necessarily regulated, but create local political problems for the facility. The U.S. EPA has indicated that future regulations on SO<sub>3</sub> emissions are to be expected.

10 It is desirable, therefore, to have an SO<sub>3</sub> flue gas system that is capable of adjusting the concentrations of SO<sub>3</sub> in a flue gas with or without an SCR installed to maintain the SO<sub>3</sub> concentration at an optimal level for increased ESP performance, without increased localized SO<sub>3</sub> emissions.

### Staging

15 Combustion staging is the process of burning a fuel, i.e., coal, in two or more stages. A fuel-rich stage, or simply, rich stage, is one in which not enough air is available to fully burn the fuel. A fuel-lean stage is one in which there is sufficient or extra air to fully burn the fuel. Staging is used in the prior art to reduce NO<sub>x</sub> by a) reducing peak temperatures (thermal NO<sub>x</sub>) and b) providing a reducing environment (NO<sub>x</sub> reduction). Macro-staging is  
20 the dividing of whole sections of a furnace into rich and lean stages and is accomplished through the use of such techniques as Over-Fired Air (OFA). Micro-staging is the creation of proximal microenvironments with functionally different characteristics, such as reduction potential, temperature, and the like. Micro-staging in a furnace can be achieved, for

example, in the first stage of the furnace through the use of Low-NO<sub>x</sub> burners with adjustment of spin-vane settings and registers. Increased staging increases the residence time in a reducing atmosphere and increases the effect of the reducing atmosphere.

Prior art has used micro-staging to reduce NO<sub>x</sub> emissions in combustion furnaces.

5 Low-NO<sub>x</sub> burners (LNB) stage by delivering high-fuel-content primary air into the furnace that mixes with secondary air flowing through one or more secondary air registers. LNB primarily use micro-staging. The flow through a LNB is designed such that the volatile components of the coal mix with the available near-field air at a stoichiometric ratio near unity (1.0), thus anchoring the flame. The net combustion in the central core near the burners  
10 is overall fuel rich and does not produce much thermal NO<sub>x</sub>, as the temperatures are low. The coal is eventually consumed over the depth of the furnace as more and more air slowly mixes into the central core. The majority of the NO<sub>x</sub> created in this region is from the fuel-bound nitrogen reacting to NO through the intermediate HCN. The rate at which the outer secondary air mixes into the core flow is set by the dampers and the spin vanes, as well as the  
15 spin vane in the coal pipe. LNB systems decrease NO<sub>x</sub> by staging since there is a continuous mixing of the rich products of combustion and secondary air throughout the combustion zone. Staging is increased by decreasing the mixing rate between the rich core flow and the outer secondary air flow.

Prior art has used macro-staging to reduce emissions in combustion furnaces. Macro-  
20 staging consists of highly mixed fuel and air in the lower furnace, mixed to a stoichiometric ratio below unity for a large part of the flow. Excess oxygen is ultimately required to assure that all of the fuel has burned and to reduce explosion risks. In a macro-staged furnace, excess air is introduced downstream of the burners. Increased staging is achieved by

increasing the residence time, temperature, or reducing quality of the combustion products in the absence of oxygen.

Prior art used both micro-staging (LNB) and macro-staging (OFA) to reduce NO<sub>x</sub> emissions in combustion furnaces. In the case of both micro-staging and macro-staging, components of each of the above are used and adjusted to achieve NO<sub>x</sub> emissions reduction.

Staging has nowhere been taught in the prior art for flue gas acidity reduction, acid dewpoint temperature control or SO<sub>3</sub> concentration control in combustion gases.

#### Summary of the Invention

The present invention is directed to method of controlling SO<sub>3</sub> flue gas concentration in a combustion process utilizing a SCR using a sulfurous fuel.

It is therefore an aspect of the present invention to provide a method of controlling SO<sub>3</sub> flue gas concentration in a combustion process utilizing a SCR using a sulfurous fuel, including the steps of:

a) providing a combustion system with low NO<sub>x</sub> burners and SCR

b) partially combusting the fuel in a first stage to create a reducing environment;

c) maintaining the reducing environment for a sufficient time period such that SO<sub>3</sub> is reduced to SO<sub>2</sub> to achieve a desirable level of SO<sub>3</sub>;

d) combusting the remainder of the fuel and combustion intermediates in a second stage with oxidizing environment;

e) reducing the remaining NO<sub>x</sub> with the SCR;

thereby reducing emissions NO<sub>x</sub>.

Another aspect of the present invention provides a method of controlling  $\text{SO}_3$  flue gas concentration in a combustion process utilizing a SCR using a sulfurous fuel, including the steps of:

- a) providing a combustion furnace with low  $\text{NO}_x$  burners and SCR
  - 5 b) partially combusting the fuel in a first stage to create a reducing environment;
  - c) combusting the remainder of the fuel and combustion intermediates in a second stage with oxidizing environment;
  - d) measuring the acid dewpoint of the flue gas;
  - e) adjusting the reducing environment in the first stage such that the flue gas acid dewpoint is
  - 10 lowered to a desirable level;
- thereby controlling the  $\text{SO}_3$  concentration of the flue gas.

Still another aspect of the present invention provides a combustion furnace operated with a method for reducing the acidity of the flue gas, the method steps including:

- a) providing a combustion system with low  $\text{NO}_x$  burners and SCR
  - 15 b) partially combusting the fuel in a first stage to create a reducing environment;
  - c) maintaining the reducing environment for a sufficient time period such that  $\text{SO}_3$  is reduced to  $\text{SO}_2$  to achieve a desirable level of  $\text{SO}_3$ ;
  - d) combusting the remainder of the fuel and combustion intermediates in a second stage with oxidizing environment;
  - 20 e) reducing the remaining  $\text{NO}_x$  with the SCR;
- thereby reducing emissions  $\text{NO}_x$ .

These and other aspects of the present invention will become apparent to those skilled in the art after a reading of the following description of preferred embodiment(s) when considered with the drawings.

#### Detailed Description of the Invention

5 In the following description, like reference characters designate like or corresponding parts throughout the several views. Also in the following description, it is to be understood that such terms as “forward,” “rearward,” “front,” “back,” “right,” “left,” “upwardly,” “downwardly,” and the like are words of convenience and are not to be construed as limiting terms. In the present invention, “reducible acid” refers to acids in which the acidity can be  
10 reduced or eliminated by the electrochemical reduction of the acid.

The present invention is directed to a method for in-furnace decrease and control of the acid dewpoint temperature using combustion staging. The present invention is further directed to a method for in-furnace reduction and control of SO<sub>3</sub> using combustion staging. Increased staging is advantageously used to simultaneously decrease the acidity, decrease the  
15 acid dewpoint temperature and reduce the SO<sub>3</sub> levels of the flue gas.

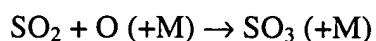
#### Acidity, acid dewpoint temperature and SO<sub>3</sub> reduction through micro-staging

Similar to how NO<sub>x</sub> is reduced back to N<sub>2</sub> in a rich “reducing” environment, SO<sub>3</sub> is reduced back to SO<sub>2</sub> in a reducing environment. With macro-staging, the center of the furnace below the OFA ports is largely fuel-rich. This staged environment can be adjusted to  
20 be even less mixed to create reducing micro-stages within the first stage of the furnace. The mixing can be reduced by reducing the spin vane velocity settings of the primary air and coal flow, or additionally or otherwise, the secondary air spin vane and register settings, thus

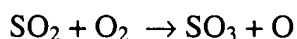


creating reducing micro-stages, or additionally or otherwise, the relative exit velocities between the primary air and coal flow and the secondary air flow can be changed.

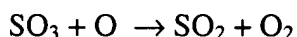
While the majority of fuel-bound sulfur forms  $\text{SO}_2$ , some forms  $\text{SO}_3$  directly during combustion of the fuel-bound sulfur.  $\text{SO}_2$  can react to form more  $\text{SO}_3$  through the following oxidative reaction:



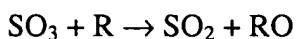
However, this three-body reaction is very slow. An additional source for  $\text{SO}_3$  production in an oxidative environment is through the reaction:



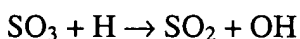
This reaction does not require three bodies to simultaneously collide; however, it is very sensitive to temperature, requiring high temperatures, and it is susceptible to reverse reaction:



None of the above three reactions occur in any significant quantity in a reducing environment due to the lack of O and  $\text{O}_2$  species. In a reducing environment, the direct conversion of  $\text{SO}_3$  to  $\text{SO}_2$  takes place through the following general “reducing” reaction:



Where R is any reducing radical species. The primary radical in fossil fuel combustion is the H radical.



Many radicals and molecules can be functional in a reducing environment; e.g., H, OH, C, CO, CH, CH<sub>2</sub>, C<sub>2</sub>H, CH<sub>3</sub>, C<sub>n</sub>H<sub>m</sub>, N, NH<sub>i</sub>, and many others.

The above SO<sub>3</sub> reducing reactions are very fast when there are significant concentrations of the reducing radicals ("R"). Sufficient concentrations exist primarily in  
5 reducing environments within the first (fuel-rich) stage of the furnace.

In a fuel-rich staged, reducing environment, oxidative chemistry terminates due to greatly decreased (extinguished) concentrations of oxidative combustion species; e.g., OH, O, O<sub>2</sub>, HO<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>, and many others. In this environment, species are very competitive for any available oxygen species. Molecules with oxygen atoms that exist in relatively small  
10 concentrations are consumed by oxygen-wanting species that exist in high concentration; e.g., the oxygen in NO is consumed by other species like C, CO, H, and CH. Molecules that have multiple oxygen atoms are particularly at risk; i.e., SO<sub>3</sub> will quickly revert to SO<sub>2</sub> through oxygen abstraction by just about anything around, most notably H atoms.

Thus, in a reducing environment, the SO<sub>3</sub> reduction reaction is very fast virtually  
15 irreversible while the reducing environment is maintained.

Surprisingly and importantly, with the present invention methods and systems, the net effect is that any SO<sub>3</sub> that is formed during combustion is quickly reduced to SO<sub>2</sub> in the first stage and SO<sub>3</sub> is not reformed by oxidation to SO<sub>2</sub> because there is not enough residence time at sufficiently high temperature in the furnace in the latter, fuel-lean stages. Thus, the present  
20 invention advantageously uses the differences in reaction rates to reduce and maintain the SO<sub>3</sub> levels in the flue gas.

Increased staging increases the residence time in a reducing atmosphere, or increases the reducing potential of the atmosphere, to decrease  $\text{SO}_3$  concentration and thereby lower the dewpoint temperature. Therefore, to increase the reduction of  $\text{SO}_3$ , the residence time can be increased or the reducing potential in the flue gases can be increased.

5 To increase residence time, several methods are available.

- 1) The distance between stages can be lengthened
- 2) The mixing can be increased for macro-staging applications
- 3) The mixing can be decreased for micro-staging applications
- 4) The mass flow between stages can be reduced (deeper staging)
- 10 5) The volumetric utilization between stages can be increased (e.g., swirl)
- 6) The pressure can be increased
- 7) The density can be increased

To increase the reducing potential in the flue gases, several methods are available.

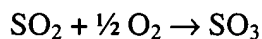
- 1) The temperature can be increased
- 15 2) The stoichiometric ratio (i.e., the air-to-fuel ratio) can be decreased.
- 3) The local fuel flow can be increased (for fixed air flow)
- 4) The local air flow can be decreased (for fixed fuel flow)

Mixing within a stage also influences the reduction process. A perfectly mixed stage with a stoichiometric mixture is the best, since these reaction conditions will give the highest temperature, while still maintaining the reducing environment; i.e., minimizing oxidation radicals like O radicals. But, since perfect mixing is impractical, in practice a stoichiometric ratio less than one is used, which minimizes the occurrence of localities with a stoichiometric ratio greater than one. However, as mixing is reduced, a longer residence time and/or higher

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temperature is needed to achieve a similar reduction of the total acidity, acid dewpoint temperature, and/or SO<sub>3</sub> concentration. However, the temperature of the combustion gases is dependent to a certain extent on the level of mixing, going down if mixing is decreased. Therefore, if an increased temperature is desired for a given degree of mixing, temperature  
5 must be increased by other means, such as preheating air, changing heat transfer characteristics of furnace, and the like. Alternatively or additionally, the residence time in the reducing environment can be increased by delaying lean stage air introduction, such as OFA injection.

Note that SO<sub>3</sub> is formed by the oxidation of SO<sub>2</sub> in a catalyst because a catalyst  
10 enables the oxidation of SO<sub>2</sub> through the following reaction:



Production of SO<sub>3</sub> in a catalyst is independent of the SO<sub>3</sub> concentration in the gas, since the catalyzed reaction is only dependent on the SO<sub>2</sub> and O<sub>2</sub> concentration. Therefore, any SO<sub>3</sub> that is reduced by the present invention independently reduces the exit SO<sub>3</sub> and is  
15 not affected by and does not affect SO<sub>3</sub> production in a catalyst.

The present invention thus provides a method for controlling and reducing flue gas acidity, specifically the flue gas concentrations of SO<sub>3</sub>, in order to beneficially (1) affect the efficiency of an electrostatic precipitator, and more particularly, (2) to reduce the concentration of SO<sub>3</sub> and other reducible acids in the flue gas in order to reduce the flue gas  
20 acidity and acid dewpoint, thereby reducing air heater pluggage, duct corrosion, and SO<sub>3</sub> emissions to the environment, which can be a source of visible plumes and localized acid rain.

In a preferred embodiment of the present invention, macro-staging to regulate furnace acidity and  $\text{SO}_3$  levels is achieved through the use of OFA. In another preferred embodiment, micro-staging to regulate furnace acidity and  $\text{SO}_3$  levels is achieved through the use of low- $\text{NO}_x$  burners. In yet another preferred embodiment, macro-staging and micro-staging through the use of OFA and low- $\text{NO}_x$  burners in combination are used to regulate furnace acidity and  $\text{SO}_3$  levels. For furnaces with SCRs in operation, the acidity is preferably regulated to reduce total flue gas acidity. For furnaces without SCRs or with by-passed SCRs, the  $\text{SO}_3$  is preferably regulated such that the  $\text{SO}_3$  levels going to the ESP enhance or favor precipitation. For current ESPs,  $\text{SO}_3$  levels between about 10 to about 15 ppm (by volume) in the exhaust is desirable for best ESP efficiency.

The dewpoint temperature is a convenient parameter for estimating and/or adjusting the reducing environment variables in order to achieve adequate reduction of acidity and/or desired  $\text{SO}_3$  levels. For a desired level of  $\text{SO}_3$  and operating relative humidity, the dewpoint can be determined and the reducing environment variable adjusted accordingly to achieve the desired dewpoint. Other methods of determining acidity and/or  $\text{SO}_3$  level can be used for the same purpose without departing from the scope of the invention.

In a preferred embodiment of the present invention, a power plant is operated to provide a deeply-staged, micro-stage or macro-stage reducing environment in the lower furnace. The OFA in the upper furnace provides the necessary oxygen to ensure an acceptable level of burnout of the remaining unburned fuel, combustion intermediates, and  $\text{CO}$ . Additionally, an SCR can be used to reduce  $\text{NO}_x$ . Thus, an embodiment of the present invention includes a combustion furnace with OFA and low  $\text{NO}_x$  burners for use with sulfur containing fuels to lower the dewpoint temperature and to reduce the  $\text{SO}_3$  concentration..

Additionally, an SCR can be provided to reduce NO<sub>x</sub>. The low NO<sub>x</sub> burners are preferably of a grade that provides adequate mixing in the primary stage to provide adequate acid dewpoint temperature reducing and SO<sub>3</sub> concentration reduction, thus permitting the use of an SCR, if necessary. Thus, an embodiment of the present invention includes a combustion  
5 furnace with high-grade low NO<sub>x</sub> burners for the purpose of reducing the flue gas acidity, lowering the acid dewpoint temperature and reducing the flue gas SO<sub>3</sub> concentration. This embodiment can further include an SCR.

An adequate reducing environment according to the present invention is one that will reduce SO<sub>3</sub> to SO<sub>2</sub> in less than about 2 seconds, more preferably, in less than about 0.5  
10 seconds. In the present invention, such a reducing environment can be achieved when the first stage flue gas temperature is greater than or equal to 900 Kelvin (1160 degrees F), more preferably greater than about 1255 K (1800 degrees F), even more preferably greater than about 1650 K (2500 degrees F). A reducing environment is one where the ratio of the concentrations of reducing radicals to oxidizing radicals is greater than about 1; more  
15 specifically, the ratio of the concentrations of H radicals to O radicals is greater than about 1. A better reducing environment is one where the ratio of the concentrations of reducing radicals to oxidizing radicals is greater than about 10; more specifically, the ratio of the concentrations of H radicals to O radicals is greater than about 10.

Thus, a method of controlling SO<sub>3</sub> flue gas concentration in a combustion process  
20 utilizing a SCR using a sulfurous fuel, includes the steps of:

- a) providing a combustion system with low NO<sub>x</sub> burners and SCR
- b) partially combusting the fuel in a first stage to create a reducing environment;

c) maintaining the reducing environment for a sufficient time period such that  $\text{SO}_3$  is reduced to  $\text{SO}_2$  to achieve a desirable level of  $\text{SO}_3$ ;

d) combusting the remainder of the fuel and combustion intermediates in a second stage with oxidizing environment;

5 e) reducing the remaining  $\text{NO}_x$  with the SCR;

thereby reducing emissions  $\text{NO}_x$ .

An alternative method according to the present invention of controlling  $\text{SO}_3$  flue gas concentration in a combustion process utilizing a SCR using a sulfurous fuel, includes the steps of:

10 a) providing a combustion furnace with low  $\text{NO}_x$  burners and SCR

a) partially combusting the fuel in a first stage to create a reducing environment;

b) combusting the remainder of the fuel and combustion intermediates in a second stage with oxidizing environment;

c) measuring the acid dewpoint of the flue gas;

15 d) adjusting the reducing environment in the first stage such that the flue gas acid dewpoint is lowered to a desirable level;

thereby controlling the  $\text{SO}_3$  concentration of the flue gas.

In another embodiment according to the present invention, a combustion furnace is operated with a method of controlling  $\text{SO}_3$  flue gas concentration in a combustion process

20 utilizing a SCR using a sulfurous fuel, comprising the steps of::

a) providing a combustion furnace with low  $\text{NO}_x$  burners and SCR

- b) partially combusting the fuel in a first stage to create a reducing environment;
  - c) maintaining the reducing environment for a sufficient time period such that reducible acids are reduced to achieve a desirable acidity concentration in the flue gas;
  - d) combusting the remainder of the fuel and combustion intermediates in a second stage with
  - 5 oxidizing environment;
  - e) reducing the remaining NO<sub>x</sub> with the SCR;
- thereby controlling the flue gas SO<sub>3</sub> levels going to the SCR.

These methods can include the step of micro-staging and/or macro-staging the first stage fuel combustion and or macro. The micro-staging can be provided through the use of low-NO<sub>x</sub>

10 burners and the macro-staging through the use of over-fired air. The fuel can be any fuel, especially carbonaceous fuels such as coal. The reducing environment can be adjusted by any of the means herein described, including adjusting the first stage residence time.

#### Examples

The following examples illustrate the results that can be achieved using methods

15 according to the present invention. Methods according to the present invention were used to control SO<sub>3</sub> levels at 3 different power plants. The experimental data shown in Tables 1 and 2 were achieved through the use of high-velocity over-fired air and were measured by third-party companies.



Table 1. Effects of Staging Depth on SO<sub>3</sub> levels at 2 different plants.

Parameters	Plant 1		Plant 2	
	Staging Depth			
	Shallow	Deep	Shallow	Deep
Load (MW <sub>net</sub> )	182	179	154	154
NOx (lb/MMBtu)	0.64	0.36	0.63	0.28
Coal %S (%)	1.22	1.22	0.87	0.87
Outlets SO <sub>2</sub> (ppm)	1100	1100	720	720
Outlet SO <sub>3</sub> (ppm)	19	5.7	11*	0.5
SO <sub>3</sub> /SO <sub>2</sub> (%)	1.7	0.52	1.5*	0.07
SO <sub>3</sub> Reduction		70%		95%

N/A – Data Not Available; \* - Estimated based on assumption that 98.5% of the sulfur in coal goes to SO<sub>2</sub> and 1.5% of the sulfur in coal goes to SO<sub>3</sub>.

For the “shallow” staging cases, the over-fired air ports were nearly closed, but still contained cooling flow (around 10% of the total air). For the “mid” staging case, the over-fired air ports made up nearly 20% of the total air flow. For the “deep” staging cases, the over-fired air ports made up nearly 30% of the total air flow. All three units were corner-fired units and the OFA system was located well above the burner zone.

Table 2. Effect of three levels of staging at a single plant (Plant 3, different from Table 1).

Parameters	Staging depth		
	Shallow	Mid	Deep
Load (MW <sub>net</sub> )	72	72	72
NO <sub>x</sub> (lb/MMBtu)	0.56	0.48	0.34
Coal %S (%)	2.85	2.85	2.85
Outlets SO <sub>2</sub> (ppm)	1856	1855	1856
Outlet SO <sub>3</sub> (ppm)	5.9	1.9	1.1
SO <sub>3</sub> /SO <sub>2</sub> (%)	0.32	0.1	0.06
SO <sub>3</sub> Reduction (vs Shallow)		68%	81%

Thus, the experimental data demonstrate the ability to regulate the SO<sub>3</sub> level using methods according to the present invention.

Certain modifications and improvements will occur to those skilled in the art upon a reading of the foregoing description. All modifications and improvements have been deleted  
5 herein for the sake of conciseness and readability but are properly within the scope of the following claims.